MODELING OF THE NON-AUDITORY RESPONSE TO BLAST OVERPRESSURE

The State of Modeling Blast Injury

ANNUAL/FINAL REPORT

James H. Stuhmiller

JANUARY 1990

Supported by

U.S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Fort Detrick, Frederick, Maryland 21701-5012

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THE STATE OF MODELING BLAST INJURY

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ABSTRACT

The background, motivation, findings, and recommendations arising from JAYCOR's modeling of the biomechanical response to blast are summarized. References are made to specific technical reports in which the detailed findings may be located.

BACKGROUND

To understand the importance of the findings of the modeling project and to appreciate the need for extending those ideas, it is necessary to review the state of knowledge of blast overpressure injury at the time that the modeling project was initiated and how the needs of Army have evolved.

TOOLS AVAILABLE FOR ASSESSING BLAST INJURY

In the early 1980's, two methods existed for assessing blast overpressure injury: one, Military Standard 1474B (Ref. 1), for use in occupational situations, and the other, the Bowen curves (Ref. 2), for use in combat conditions.

Mil. Std. 1474-B is a standard developed for predicting auditory hazard based on observed values of peak pressure level and duration. It contains the so-called "Z-line," above which no soldier should be exposed because of possible nonauditory injury that no amount of hearing protection could prevent. The nature of that injury is unspecified and the curve was not based on any observational data, although it might have reflected the intuition of the committee. The other curves in the standard were based primarily on small calibre weapons and, at the time of its creation, the Z-line was well removed from any operational weapon system.

The second method available was Bowen's curves, again, relations in terms of peak pressure and duration, albeit a duration with a slightly different definition. These curves correlate the blast overpressure conditions for which 50% of the animal subjects died (LD_{50}). The data was collected primarily for the Defense Nuclear Agency (DNA) in order to describe nuclear blast effects. All of the tests were made in the free field with large explosives, producing a family of blast curves that are very regular and readily described by two parameters: the peak pressure and the positive overpressure duration. The blast was always unidirectional and of such long duration that the subject was completely immersed in the overpressure. Because there are only two degrees of freedom to the blast wave, it was possible to study the effect extensively, even using a variety of species. Based on this correlation, another correlation was proposed for the onset of injury to the lung, however the relation was not based on injury data.

SITUATIONS OF INTEREST TO US ARMY

The blast overpressure exposures of concern to the US Army, however, do not match either of these categories.

On one hand, for occupational exposures during training, large calibre field artillery produce pressure traces in the crew areas that exceed the Z-line. These signals are similar to free field explosions at intermediate distances, that is, they have longer durations than small calibre fire and yet shorter durations than the conditions studied for DNA.

On the other hand, there is a growing need for injury assessment from blast in armored fighting vehicles. The blast signals in these cases are characterized by relatively low peaks but long, reverberant durations. The signals follow no obvious pattern and can vary considerably from one location to another in the vehicle, earning them the name "complex."

The results of applying the conventional tools to these situations was disconcerting. The large calibre weapons clearly exceed the allowable limits, although there was a general feeling that no acute injury was occurring. Still, for occupational health, chronic injury must be considered. When the Bowen methodology was applied to the behind armor data, the results were completely arbitrary. If the methodology were followed rigorously, using the peak pressure and the time to the first zero overpressure, the curves would consistently underpredict injury. If the "sensible" duration were selected, that is, the time at which the overpressure sensibly vanished, the injury predictions were overpredicted. A variety of ad hoc rules were suggested to apply the Bowen curves in a way that gave "reasonable" answers. The results were not satisfying.

US ARMY RESPONSES

To address these issues, the Army took several direct actions.

Man-rating studies were initiated for the various weapon systems that exceeded the Z-line. In very careful tests, hearing decrements were measured after exposure to various numbers of firings and an upper limit on exposures per day was established. Needless to say, these studies are very long and costly. Laryngoscopic examinations were used to detect precursory nonauditory injury.

Animal studies were undertaken at the Kirtland Blast Overpressure Site to extend the understanding of combat level exposures. Data taken under conditions more relevant to conventional weapon exposure produced threshold lung injury curves in conflict with the predictions of Bowen. There are situations, for example, in which one correlation predicts no injury, while the other predicts severe injury.

The same studies revealed another effect, that wearing a Kevlar ballistic garment significantly increases the occurrence and severity of lung injury. Naturally, none of the existing methodologies accounts for, or even acknowledges, such an effect.

Animal testing was used in the first defeated vehicle tests, but, for a variety of reasons, was discontinued before it was possible to develop any substantial understanding of how injury estimates should be made. Subsequently, tests were conducted at the Kirtland site using various sized and shaped enclosures. Two trends became immediately clear. First, it was possible to produce extreme injury in an enclosure for a charge and distance combination that in the free field would produce no injury at all. Second, it was very difficult to design tests that produced a desired level of injury, for example, threshold. One tended to get a lot or nothing. When explosives more representative of anti-vehicle weapons were used, the results were even less predictable.

STATEMENT OF PROBLEM

It became clear that there was no fundamental understanding of the injury process and, therefore, no way to reliably extrapolate previous animal tests. The reliance on the empirical experience that had been gained for long-duration, free field blast waves and that was encapsulated in the two-parameter Bowen correlations of injury not only could not be applied, but was leading the testing effort down blind alleys.

Field testing had never been conducted with the goal of systematically developing such an understanding. Each test series had been motivated by some specific application. Consequently, grading of injury and description of the blast overpressure varied for test to test. In fact, the data had never been systematically compiled and analyzed.

Furthermore, animal testing is becoming less desirable. Complex waves present too many possibilities to approach in a brute force way. With limited time and resources, it is necessary to have a more scientific approach to the task of estimating blast overpressure injury.

MODELING EFFORT

JAYCOR has been involved in the assessment of blast injury for the US Army Medical Research and Development Command since 1979. We began by assisting WRAIR in the measurement and interpretation of field data for the first howitzer tests. At each step, it became clear that field or laboratory data in itself could not answer the questions at hand. Consequently, we have developed models for the blast field around weapons, the propagation of blast to and around bodies, and the dynamic response of the biological system all the way down to the tissue level. The discussion below summarizes that effort, its goals, accomplishments, and unresolved issues. An overview of the modeling effort at the beginning of the current project can be found in Reference 18.

GOALS OF THE PROJECT

The modeling effort has two principal goals. The first is to develop a true, mechanistically correct understanding of the processes responsible for blast overpressure injury. The basic tenet of the technical approach is that injury should correlate with stresses acting on the tissue no matter what the nature of the external stimulant. This part of the project can be characterized as a basic research endeavor.

The second goal is to provide a best-estimate capability to predict injury. This objective reflects the reality that understanding will always be growing and requirements evolving, but that the previous methodologies are inadequate and that there is an immediate need for better founded estimates.

SCOPE OF THE WORK

The scope of the project was broad. All nonauditory organs affected (tympanic membrane, upper respiratory tract, lung, and the gastrointestinal tract) were to be considered. Separate research efforts were established for each organ, although the lung received the majority of the effort.

Another aspect of the project was to interact with and support research programs in-house at WRAIR and field testing at the Kirtland site.

Finally, priorities were set quarterly at the project review meetings to guarantee that the effort was addressing the Army's immediate needs, while maintaining a vigorous research program. For example, URT modeling, which was not given much importance at the beginning of the project, was pursued intensively at the time that WRAIR needed to modify the damage risk criteria for occupational exposure. Complex wave analysis became the principal theme of the later stages of the project as the inadequacy of the Bowen model and the urgency of the behind armor effort became apparent.

ACCOMPLISHMENTS

We have been able to express equal-injury conditions in terms of equal-tissue response for the URT, TM, and Lung and we have provided simple, practical tools for estimating gross injury that replace both the Z-line of the Mil. Std. and the Bowen curves.

A brief discussion highlighting some of these accomplishments follows.

BALLISTIC GARMENT EFFECT

Definitive laboratory tests have been conducted that show that the ballistic garment increases the load delivered to the body. As a by-product of our investigation into parenchymal dynamics, we found a mechanical equivalent to the jacket effect that allows a controlled study of the phenomena (Ref. 3). With this insight and data, a computational model was developed that could be used to guide the design of a better garment and could form the basis for a model for the prediction of enhanced injury.

TYMPANIC MEMBRANE

A finite element structural model of the tympanic membrane was developed. When the model was subjected to a pressure loading it responded dynamically, producing regions of stress concentration near the manubrium and in radial bands outward toward the tympanic ring. These stress concentration points correspond to locations of observed membrane rupture in animals.

Based on the full structural model, a simplified response model was constructed so that dynamic analyses of blast loading could be readily made. Previously measured properties of the membrane elasticity and breaking strength of the collagen fibers were used to establish a range of tissue stresses likely to cause rupture.

The model was compared to the extensive data of James, et al., in which load at the membrane and damage to cadaver ear drums were measured. The occurrence and severity of tympanic membrane rupture were found to correspond to the tissue stress calculated. Details are found in Reference 4.

UPPER RESPIRATORY TRACT

A simplified structural model was developed to transform the pressure loading forces on the external surface of the neck into tissue stress on the inner tracheal wall. Measurements of blood vessel critical stresses were used to establish failure limits.

Working together with Ken Dodd of WRAIR, data on upper respiratory tract injury from Kirtland field tests were compiled and graded. Data from single shot exposures confirmed the predictions of the structural model.

To explain the blast levels required to produce injury during *multiple* shot exposures, a model of material failure patterned after fatigue failure was conceived. Using values characteristic of other structural materials, reduced strength estimates were made for repeated exposure. When compared to the entire data base, injury from 1, 5, 20, and 100 shot exposures could all be predicted from the same material properties model.

Further investigation of the model's predictions reveals that, for simple free field explosions, the threshold for URT injury corresponds very closely to the Z-line of Mil. Std. 1474B.

It is now possible to replace the nonauditory criteria of the Mil. Std. with a unambiguous and tested methodology that not only applies to free field exposures, but can be used in complex wave environments to estimate occupational hazard. Details may be found in Reference 5.

LUNG

The lung received the largest research effort and, consequently, had the greatest number of findings and results. A brief synopsis of those results follows.

Basic Research Findings

Although the functional nature of the lung is well understood, the mechanical properties of the parenchyma, especially under dynamic conditions, was not well understood. In a series of *in vitro* tests with lung tissue, all of the viscoelastic properties were determined. The most dramatic of these is the combination of relatively high mass density and high compressibility which leads to very slow propagation of pressure waves. This slow response of the lung to mechanical motion is the primary reason for injury at the pleural surface. Other properties measured, included the tissue stress-strain relations, which play a role in determining the mechanical failure limits of the tissue.

Working together with Ken Dodd of WRAIR, a series of field studies was conceived, executed, and analyzed that revealed the dynamic character of the thorax. Surprisingly, it was found that the thorax response is dominated by the inertia of the chest wall, rather than any elastic forces from the rib cage. This result is in sharp contrast to dynamics under blunt trauma. This finding allowed a series of computational models of the thorax and lung to be constructed. Details may be found in Reference 6.

Using the knowledge of the thorax mechanics and the finding that foam has the same mechanical properties as the parenchyma, a mechanical surrogate of the chest wall-lung tissue was constructed. With this device it is possible to study thorax and pleural dynamics with complete control. Details may be found in Reference 3.

One finding of the surrogate tests was that under sufficiently large chest wall velocities, the parenchyma develops a pressure concentration similar to a shock wave in a gas. Associated with this "parenchymal shock" is a loss of mechanical energy, a dissipation that, in an living organ, might correspond to damage.

Again, field tests were conceived and during one of the last test series made at Kirtland, direct evidence, from pressure probes inserted into the lung, was found for the occurrence of a parenchymal shock near the pleural surface.

The parenchymal shock was also simulated in our lung tissue computational model and a simple relation between parenchymal pressure and chest wall velocity was developed. That simple relation made it possible to develop a single-degree of freedom model of the thorax that predicts the pleural pressure.

Further investigation revealed that the total work done against this irreversible force correlates well with pleural damage seen in field tests. In order to test this finding, a considerable amount of effort was exerted into collecting and compiling the existing lung injury data. That collection, while far from acceptable in terms of its qualification, nonetheless shows the validity of the so-called "work correlate of injury."

With the work correlate, it is possible to bring together all of the previous injury data. Differences between the WRAIR and Bowen results can be understood. Multiple-shot and multiple-exposure data follow the same pattern. Even when the correlate is applied to explosions within enclosures the correlation is quite satisfactory. Details may be found in Reference 7.

Finally, direct investigation of the injury mechanism with microphotography and scanning electron microscopy has been performed. Blast injured lung tissue shows mechanical damage in the regions where gross hemorrhage is observed. To complete the understanding of lung injury it is necessary to relate the mechanical correlate directly to the material properties of the parenchyma. Details of the current findings are in Reference 8.

Computational Models

The findings on the dynamics of the thorax and lung have been translated into three levels of computational models.

The most elaborate is a multidimensional finite element model (FEM) that can resolve the dynamic motion and pressure wave propagation in the parenchyma, taking into account the geometry of the lobes and the nature of the various bounding surfaces. This model has qualitatively shown the most likely locations of injury: the pleural surface on the blast side, the tips of the lobes, and the regions around the heart and the spinal process. Details are reported in Reference 9.

The second model follows the dynamic motion in a single spatial direction, perpendicular to the lung surface. This model can employ greater spatial resolution at reasonable cost and, therefore, has been used to study the "parenchymal shock" phenomena. This model is also applicable to the Kevlar jacket investigation. Details are described in Reference 6.

One application of the one-dimensional thorax/lung model has been to understanding injury from multiple explosions separated in time by a few milliseconds. The model shows that an excellent correlation exists between the predicted peak pleural pressure and the observed increase in lung weight. A description of this application may be found in Reference 19.

The third model follows the dynamic motion at a single spatial point on the pleural surface. Because of the considerable simplification afforded a single degree of freedom model, it is possible to readily solve the equations and compare the results with a wide range of field data. The model's prediction of pleural injury correlates very well with graded injury from necropsy reports for a wide range of circumstances: single, multiple, and repeated explosions in the free field, as well as a variety of explosions in an enclosure.

Applications

The research into thorax dynamics and lung injury produced several products that were not originally anticipated in the project.

a. Compilation of Field Data on Injury

In the process of testing the validity of the injury prediction model, we found that the existing data had never been assembled and tabulated. Consequently, we compiled all of the readily available literature, data records, and informal working papers and published these findings in a single source. Electronic forms of the data were also produced that could be manipulated with the analysis software. A compilation of the data as of early 1989 is contained in Reference 10. The reader should be aware that a more extensive collection is being assembled and that the data in Reference 10 has not been qualified against the ongoing source material.

b. Lambdroid Test Fixture

The modeling work demonstrated the need for better information on blast load distribution on the animal. JAYCOR then conceived a simple test fixture, with multiple pressure probes, that could be used to simulate the geometry of a sheep or a man and collect, in one pass, all of the relevant load data. That device, nicknamed Lambdroid, has become a standard field measurement device. Details are contained in Reference 11.

JAYCOR also constructed a smaller, lightweight version, "Lambdroid, Jr.," that could be placed within vehicles. In time, this device will probably become the standard by which blast measurements are taken.

c. VU Package for Field Data Analysis and Reduction

In the process of supporting field studies, it became evident that the existing data analysis process was too slow to allow the investigator in the field to understand the results of his tests and make modifications. For example, summer study data was not fully reduced until after the study was completed and the only recourse was to modify plans for the next summer.

JAYCOR analyzed the problem and wrote special data acquisition and analysis software for use in the field. Customized to the acquisition hardware in use by WRAIR, this software, VU, allowed full analysis of all data within minutes of a shot. Problems could be detected and corrected without losing an entire series.

d. Computational Model of Blasts in an Enclosure

To understand the "complex wave" data being collected in behind-armor studies and to provide loading histories for estimating injury in new situations, JAYCOR developed a method-of-images model of the blast field inside an enclosure. The details of the model and its comparison with experimental data are found in Reference 20.

The VU package has been continually expanded and upgraded and is in its sixth major version. It now has full data base features to allow data to be stored, recalled, compared, integrated, etc. Details may be found in Reference 12.

GASTROINTESTINAL TRACT

Injury to the gastrointestinal tract has received less attention because its consequences are believed to be longer term and less life threatening. As a result, little had been done to understand and correlate the occurrence of injury, despite the considerable amount of necropsy data available.

JAYCOR's investigation began by establishing, with direct observation of surrogates and *in vitro* preparations, the correlation of gas bubble location and injury site. With a firm knowledge of the nature of the injury process, a step-by-step research plan was conceived and executed.

In order to maintain an environment that preserves the critical *in vivo* characteristics of the GI tract, most importantly the perfusion of blood, yet allows the direct observation and intervention required to quantify the injury process, a special surgical technique was developed. This procedure, designed for rabbit, allows the animal's heart to continually perfuse the intestinal tract while the tract has been removed to a special chamber where blast exposure can be simulated. See Reference 13.

Using this perfusion technique, data was collected that defined the typical locations and nature of injury and the local bubble parameters that appear to control the magnitude of injury. Next, materials were tested and selected that gave the same dynamic response as the intestinal sections. Comparisons were made to ensure that the surrogate model in the configuration of intestinal tract also responded as the biological system.

Using the surrogate model, extensive tests were conducted to determine all of the relevant mechanical properties affecting the bubble dynamics. Bubble volume and shape, curvature and strength of the intestinal section, and proximity of sections to neighboring sections and other organs were all assessed with the surrogate model. Details may be found in Reference 14.

From these results, an understanding of the abdominal dynamics in the neighborhood of gas-containing sections emerged. Based on this understanding, a calculational model of the processes was constructed and compared with the surrogate data. With this model, abdominal pressure histories can be translated into local bubble motion and eventually strain rates of the intestinal tissue. Details are reported in Reference 15.

Material properties tests were conducted to determine the elastic properties of various gut sections and to estimate their limiting strengths. This failure limit determines the injury curve, once the relation between the external blast and the abdominal pressure is known. Rupture strength findings are contained in Reference 16.

Working together with WRAIR, field tests were conceived to produce the desired abdominal pressure data. The initial results, from tests piggy-backed onto other studies, were inconclusive because of difficulties in surgically implanting the pressure probes and in knowing the environment at the probe. The signals change dramatically if the probe is in or out of a gas bubble.

To support the field effort, JAYCOR conceived, designed, and tested in the laboratory an apparatus, Probe-in-Balloon (PiB), that can accurately measure the pressure and control the bubble environment. Unfortunately, the field testing was never resumed so that the critical abdominal data was not collected. JAYCOR also developed and tested a variety of laboratory test techniques for assessing gastrointestinal injury. A description of these techniques is found in Reference 17.

UNRESOLVED ISSUES

This research effort has not only achieved its original objectives of providing a mechanistic understanding of injury processes and of providing a predictive methodology, but has identified other areas of concern and the means to find their resolution.

UNDERSTANDING OF GI INJURY

The mechanistic models required for GI injury prediction are incomplete because effort was redirected to more pressing issues. The technology for completing the understanding exists and the technical approach have been formulated.

The model for abdominal response has been defined but not completed and validated. This model will connect the external blast field to the local pressure in the vicinity of an air-containing gut section. The model for the dynamics of the gas bubble has been developed and validated in detail against surrogate tests. The model for the GI tract section response has been formulated, but not completed and validated. This model translates the gas bubble dynamics into stresses in the tract tissue. Finally, a model for blood vessel rupture, the "aneurysm model" has been proposed. This model will connect the local tissue dynamics to the stresses in the vascular system that leads to rupture. If this modeling effort were completed, a predictive methodology for GI injury would be available.

GI INJURY DATA BASE

Gastrointestinal injury data from the Kirtland test site has not been compiled, qualified, or analyzed. Detailed necropsy data and notes exist and were collected at the time the lung pathology data was taken, however, no systematic reporting of the data has ever occurred.

CORRELATION WITH OCCURRENCE OF LUNG INJURY

In addition to providing a means of verifying the GI injury model, a data base of necropsy data containing both lung and GI injury would allow the occurrence of combined injury to be correlated with blast conditions.

PREDICTION OF TMR

The tympanic membrane rupture model provides an estimate of gross injury but would not be accurate near threshold values because it lacks an outer ear and an ear canal model. It is known that the ear canal modifies the pressure signal and the pinna introduces directional effects.

Another model that should be added to the TMR methodology is one describing the effects of hearing protection. Good observational data on these effects can be obtained from the man-rating studies. These data could also be used to validate an ear canal model containing hearing protection.

CORRELATION WITH AUDITORY INJURY

The success of the tympanic dynamics model suggest that good estimates of the energy delivered to the cochlea could be produced. Currently, there is a gap in auditory research at high overpressure because the linear transfer models don't apply when the system is driven into a range of nonlinear mechanical response. Addition of a mechanical model of the ossicular chain to the current structural model offers great promise in filling this gap. Data from the man-rating and future walk-up study tests could provide the necessary model validation.

KEVLAR JACKET EFFECT

The ballistic garment has been conclusively shown to enhance blast overpressure injury. The root mechanisms of the load enhancement process have been identified and surrogate and computational models exist for the systematic study of the process. What is missing is to apply these tools to produce an understanding that can be incorporated into the injury prediction software package and can be used to guide future design requirements of materiel.

TISSUE LEVEL INJURY MECHANISM

Current research has provided three critical pieces of information on the mechanism of lung injury. First, rapid distortion of the parenchyma leads to "shock" waves in the lung tissue and the irreversible work associated with the resulting forces correlates with pleural injury. Second, microphotographs of the injured pleural regions shows mechanical damage to the parenchyma. Third, mechanical properties measurements of lung tissue show a limiting stress, perhaps related to structural failure of the tissue, for strains comparable to those estimated for blast overpressure injury.

The implications of these findings is that there is a direct and quantifiable connection between the mechanical aspects of the tissue response (which can be calculated with existing models) and injury. If this connection could be determined in a quantified way, the prediction of injury could be generalized to all parts of the lung.

Furthermore, an understanding of the tissue level changes brought about by blast overpressure injury would be the first step toward explaining the enhancing effect that exercise has on blast injury of the lung and a means for determining the combined injury potential of blast overpressure and toxic gas exposure.

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